Unveiling the multi-wavelength phenomenology of Anomalous X–ray Pulsars

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Abstract. During 2002-2003 the number of IR-identified counterparts to the Anomalous X–ray Pulsars (AXPs) has grown to four (4U0142+614, 2E2259+584, 1E 1048-59 and 1RXS J170849-400910) out of the six assessed objects of this class, plus two candidates. More importantly, some new common observational characteristics have been identified, such as the IR variability, the IR flattening in the broad band energy spectrum, the X-ray spectral variability as a function of pulse phase (which are not predicted by the *magnetar* model), and the SGR–like bursts (which can not be explained in terms of standard accretion models).

We present the results obtained from an extensive multi-wavelength observational campaign carried out collecting data from the NTT, CFHT for the optical/IR bands, and XMM, Chandra (plus BeppoSAX archival data) in the X-rays. Based on these results and those reported in the literature, the IR-to-X-ray band emission of AXPs has been compared and studied.

1.   Introduction

It is now commonly believed that Soft γ–ray Repeaters (SGRs) are magnetars — neutron stars powered by their strong magnetic fields (B>10^{14} Gauss). AXPs have been linked to SGRs because of similar timing properties, namely large periods (P; in the 5-12s range) and large period derivatives ($\dot{P}$; Thompson & Duncan 1993 and 1996). However, what differentiates these two seemingly dissimilar objects is, at present, unclear. Nonetheless, there is a growing group of radio pulsars (Camilo et al. 2000) with similarly long periods and with inferred magnetic field strengths approaching 10^{14} G. These pulsars possess no special attributes linking them to either the AXPs (no steady bright quiescent X–ray emission; Pivovaroff, Kaspi & Camilo 2000) or to the SGRs (no bursting history). Thus periodicity alone does not appear to be a sufficient attribute for classification. Conversely, a very high magnetic field strength cannot be the sole factor governing whether or not a neutron star is a magnetar, a radio pulsar or in a binary system. One possibility is that AXPs and SGRs are linked temporally. Specifically, three out of the six AXPs are associated with supernova remnants (SNRs) whereas only SGR 0526–66 has a plausible SNR association (Gaensler et al. 2001). Taken at face value, these data suggest that AXPs evolve into SGRs. However, this hypothesis has at least two severe problems (Kulkarni et al. 2003). First, the rotational periods of SGRs are similar to those of AXPs, about 10-s. Second, inferred magnetic field strengths of SGRs are similar to (and perhaps even larger than) those of AXPs (Mereghetti et al. 2002).

The recent detection of X–ray bursts from 1E 2259+586 and 1E 1048.1–5937 has strengthened the possible connection of AXPs with SGRs (Kaspi & Gavriil 2002; Gavriil et al. 2002). In the case of 1E 2259+584, IR variability of the counterpart has been detected few days after a strong X–ray bursting activity. Also the variability of the IR counterpart to 1E 1048.1–5937 is thought to be related to X–ray variability (Israel et al. 2002). Although these new properties open a new horizon in the field, we do not understand what specific physical parameter(s) differentiates AXPs from SGRs.

Evidence for flattening (or excess) of the flux in the IR band, with respect to a simple blackbody component extrapolated from the X–ray data, has been reported in four AXPs, namely 1E 2259+586, 1E 1048.1–5937, 4U 0142+614 and 1RXS J1708–4009 (Hulleman et al. 2001; Wang & Chakrabarty 2002; Israel et al. 2003a and 2003b). The magnetar scenario (in its present form) does not account for the observed IR emission or variability in AXPs and no predictions can be, therefore, verified. On the other hand, the accretion models fail in accounting for one of the main feature of SGRs, and recently AXPs, that is the bursts. In conclusion, none of the proposed theoretical models (at least in their present form) seem to be able to account simultaneously for the IR, optical and X–ray emission of AXPs. In this respect the IR emission from AXPs/SGRs may play a key role in the study and understanding of these sources.

2.   *Chandra* HRC–I and IR adaptive optics observations

The IR-to-X–ray data we relied upon have been obtained as a part of a joint ESO/*Chandra* large project aimed at the identification and study of the opti-
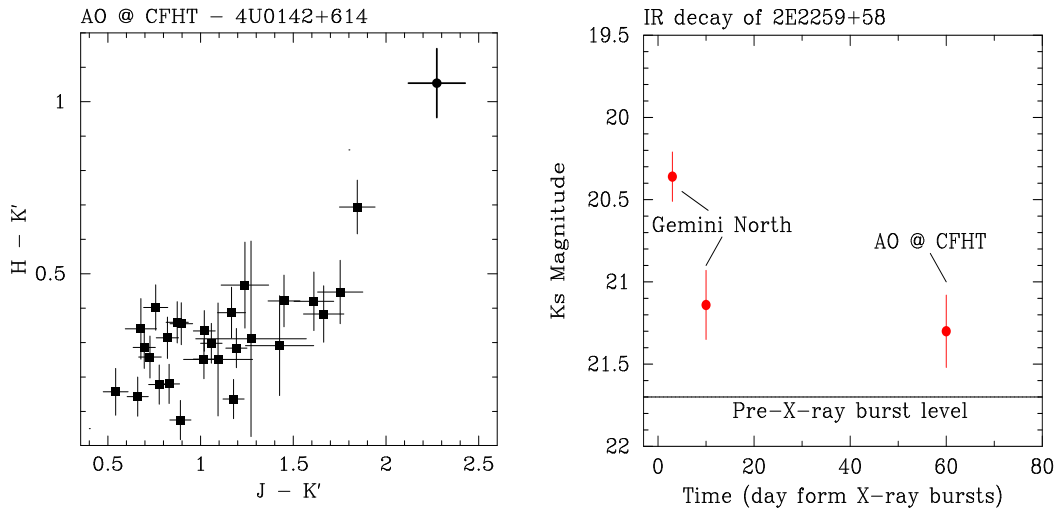
Figure 1. IR color–color diagram obtained for the region (radius of $30''$) around the position of 4U 0142+614 and based on adaptive optics observations carried out on August 2002 from the CFHT (left panel). The counterpart (in the upper right corner) clearly stands out with respect to the other objects in the field of view. IR decay "lightcurve" of 1E 2259+586 inferred by using the CFHT data presented here and those in literature (Kaspi et al. 2003; right panel).

cal/IR counterparts of AXPs in the southern sky, and the study of the spatial distribution of X–ray emission from AXPs. About 10ks *Chandra* observations have been obtained for 1RXS J170849−400910 and 1E 1048.1−5937, while 20ks have been devoted to AX J1844−0258. In all cases the HRI–I instrument has been used in order to obtain the most accurate X–ray position.

Optical and IR data have been obtained for all the known AXPs from the 3.5-m New Technology Telescope (NTT, La Silla, Chile; SOFI and SUSI2 instruments), the 4-m Canada France Hawaii Telescope (CFHT with OAB), and more recently from the Very Large Telescope (VLT with FORS and ISAAC).

The results obtained for 1RXS J170849−400910 and 1E 1048.1−5937 have been already presented elsewhere and concern the identification of the likely IR counterpart of 1RXS J170849−400910, and the detection of IR variability from the IR counterpart of 1E 1048.1−5937 (Israel et al. 2002, Israel et al. 2003a).

4U 0142+614 has been observed at the CFHT in the J ($\sim$3000s effective exposure time), H and K' ($\sim$4000s) bands, and thanks to the adaptive optics we obtained a source PSF of $\sim0''\!.16$. After standard photometric reduction we inferred the following magnitudes: $J = 22.3 \pm 0.1$, $H = 21.1 \pm 0.1$ and $K' = 20.0 \pm 0.1$ (Israel et al. 2003b, in preparation). Figure 1 (left panel) summarises the photometric results; the IR counterpart of 4U 0142+614 clearly stands out in the color-color diagram ($J - K' = 2.3$) with respect to the other objects in the field of view.

K' band observations at the CFHT have been also carried out for 1E 2259+586 for a total exposure time of $\sim$7300s, 2 months after the detection
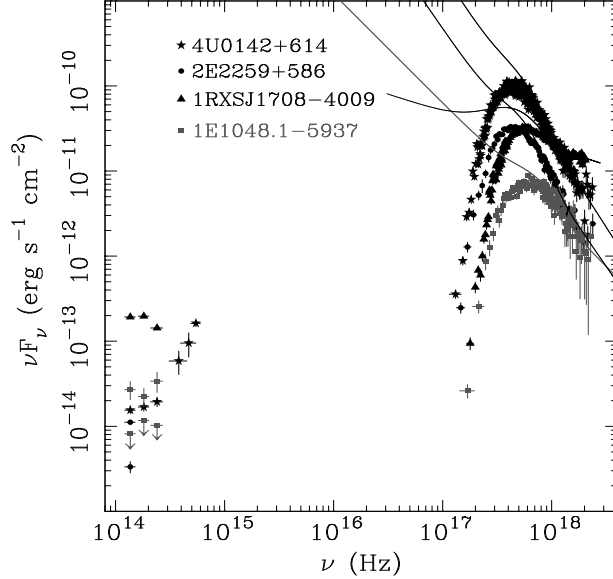
Figure 2. Broad band energy spectrum of AXPs. X–ray raw data are taken from the medium and low energy instruments on board *Beppo*SAX while the solid upper curves are the unabsorbed fluxes for the black body plus power law model. On the lower left corner of the plot are the optical/IR unabsorbed fluxes.

of SGRs-like burst activity from the X–ray pulsar (Kaspi & Gavriil 2002). Also in this case, thanks to the relatively narrow PSF achieved with the adaptive optics ($\sim$0$.\!\!''$19) we were able to detect the IR counterpart at a K' magnitude level of 21.31±0.24 (about 0.4 magnitudes brighter than the magnitude reported by Hulleman et al 2001; see also Figure 1, right panel). This result implies that after 2 months the IR "activity" of 1E 2259+586 is still present.

Based on the above results and those already present in literature, we have plotted the broad band energy spectra of the four AXPs for which the IR/optical counterparts are known. In Figure 2 we show the IR-to-X–ray spectra (X–ray raw data are absorbed; solid lines represent the unabsorbed models). It is worth noting the scatter in the X–ray unabsorbed fluxes that is of a factor of about 10. Also the IR fluxes show a relatively large scatter of values. Moreover, we note that 1RXS J170849−400910 is by far the AXP which most deviates from the other sources, both in the X–ray and in the IR bands. Finally, the IR flux values of 4U 0142+614 presented here clearly show a deviation from the black body component which was originally used to fit the optical fluxes (Hulleman et al. 2000). Given the extremely high values of the extinction in the direction of the AXPs, we note that the flux ratio F_X/F_{IR} have a large uncertainty, depending on the assumed X–ray energy interval.

3. The debated case of AX J1844−0258

AX J1844−0258 is a candidate AXP since the discovery of 7s X–ray pulsations in a 1993 ASCA dataset (Torii et al. 1998). The source was observed once again
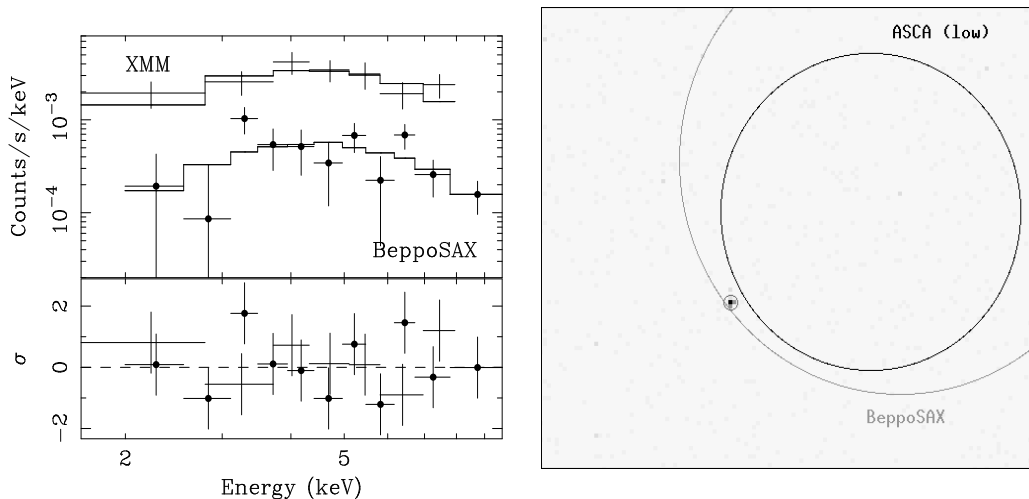
Figure 3.   XMM EPIC and BeppoSAX MECS spectra of AX J1844−0258 fitted with an absorbed power law model (left panel). The *Chandra* HRC-I image is shown with superimposed the ASCA and BeppoSAX positional uncertainty regions at the 90% confidence level ($20''$ and $35''$, respectively; right panel).

with ASCA a year later and was detected at flux of a factor of about 10 fainter. No periodicity was detected (Vasisht et al 2000). Therefore, its association to the AXP class was based merely on the period and spectral parameters of the source in the "high" level.

In order to clarify the nature of AX J1844−0258 we requested 90ks-long BeppoSAX, 20ks HRC–I *Chandra*, and 25ks XMM observations. Moreover we obtained optical and IR images from the NTT. In all X–ray images we detected only a relatively faint object, the position and count rates of which were consistent with those of the second ASCA observation. In Figure 3 (left panel) we show the BeppoSAX and XMM spectra of AX J1844−0258 which are well fitted with an highly absorbed ($N_H \sim 5 \times 10^{22}$ cm^{-2}) power law ($\Gamma = 1.2 \pm 0.8$) or alternatively a black body with a characteristic temperature of 1.0 ± 0.5 keV. In both cases the unabsorbed luminosity is in the $10^{33} - 10^{34}$ erg s^{-1} range (assuming 7 and 15 kpc as fiducial distances).

Due to the slightly off-axis position of the target in the *Chandra* pointing and to its faintness, the best position is a circular region with a radius of about $1''$. The optical/IR observations revealed no peculiar objects within the uncertainty region down to a limiting H magnitude of about 21. Spectroscopic VLT data of the closest object to the *Chandra* position have been carried out and the analysis is in progress end will be reported elsewhere.

References

Camilo, F., et al. 2000, ApJ, 541, 367

Gaensler, B., et al. 2001, ApJ, 559, 963

Gavriil, F., et al. 2002, Nature, 419, 142

Hulleman, F., van Kerkwijk, M.H., & Kulkarni, S.R. 2000, Nature, 408, 689

Hulleman, F., et al. 2001, ApJ, 563, L49

Israel, G.L., et al., 2002, ApJ, 580, L143

Israel, G.L., et al., 2003a, ApJ, 589, L93

Israel, G.L., et al., 2003b, in preparation

Kaspi, V.M., & Gavriil, F., 2002, IAU Circ. 7924

Kaspi, V.M., et al. 2003, ApJ, in press, astro–ph/0304205

Kulkarni, S.R., et al. 2003, ApJ, 585, 948

Mereghetti, S., et al. 2002, in "Neutron Stars, Pulsars and Supernova Remnants", eds. W. Becker, H. Lesch & J. Trümper (Garching: MPE-278), p.29, astro-ph/0205122

Pivovaroff, M.J., Kaspi, V., & Camilo, F., 2000, ApJ, 535, 379

Thompson, C., & Duncan, R.C. 1993,ApJ, 408, 194

Thompson, C., & Duncan, R.C. 1996,ApJ, 473, 322

Torii, K., et al. 1998, ApJ, 503, 843

Vasisht, G., et al. 2000, ApJ, 542, L37

Wang, Z., & Chakrabarty, D., 2002, ApJ, 579, L33